

## MSSM: SOURCE FOR GENERATING PERTURBATIONS

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In this talk I describe how MSSM flat directions act as a source for generating all matter and scale invariant adiabatic density perturbations with a spectral index slightly depending upon the choice of a particular flat direction.

### 1. Introducing MSSM flat directions

Supersymmetry (SUSY) is by far the best candidate beyond the electroweak Standard Model. It explains the hierarchy in scales, resolves the Higgs stability, gives rise to gauge unification, and foremost it is a building block for superstring theories <sup>1</sup>. In this talk I will concentrate upon its cosmological consequences <sup>2</sup>. Cosmology is a booming area where recent satellite based experiments have given a new precession measurements of various cosmological parameters <sup>3</sup>.

The highlight of the talk is to show that Minimal Supersymmetric Standard Model (MSSM) can act as a source for all matter and primordial density perturbations. The is because MSSM possesses F-and D-flat directions (made up of squarks and sleptons). For a generic SUSY model, with chiral superfields  $X_i$ , it is possible to find out the directions, where  $N = 1$  SUSY potential,  $V = V_F + V_D$ , vanishes identically, by solving simultaneously

$$D^a \equiv X^\dagger T^a X = 0, \quad F_{X_i} \equiv \frac{\partial W}{\partial X_i} = 0. \quad (1)$$

Field configurations obeying Eq. (1) are called respectively D-flat and F-flat. These directions are parameterized by gauge invariant monomials of the chiral superfields. A powerful tool for finding the flat directions has been developed in Ref. <sup>4</sup>, where the correspondence between a gauge invariant monomial and flat directions has been studied. Its generalization to gauge invariant polynomials can be found in Ref. <sup>5</sup>. These flat directions act as a cosmic condensate during inflation. There are various cosmological consequences which I will *not* discuss here, interested readers are referred to Ref. <sup>2</sup>.

## 2. Inflationary paradigm

Inflation is the most favored paradigm for the early Universe. Besides making the Universe flat, homogeneous and isotropic, it is the only causal mechanism which stretches the fluctuations (below the Planckian energy density) outside the horizon. After inflation these modes re-enter and act as seeds for the structure formation. In spite of all these successes the identity of inflaton is not known, nor its potential. It is often regarded as an absolute gauge singlet. Inflationary sector is almost like a dark energy sector, which is hard to pin down without a knowledge of full quantum nature of gravity. Very recently it has been possible to show that gauge invariant flat directions can give rise to inflation in  $SU(n)$ ,  $SO(n)$  theories<sup>6</sup>.

## 3. Forming a cosmic condensate

During inflation squarks and sleptons are free to fluctuate along the flat directions and form scalar condensates. Because inflation smoothes out all gradients, only the homogeneous condensate mode survives. However, like any massless scalar field, the condensate is subject to inflaton-induced zero point fluctuations which impart a small, and in inflation models a calculable, spectrum of perturbations on the condensate. During inflation the dynamical evolution of these condensates is frozen, but after inflation their dynamics play important role<sup>2</sup>.

In addition to the usual softly SUSY breaking, the non-zero energy density of the early Universe also breaks SUSY, in particular during inflation when the Hubble expansion dominates over any low energy SUSY breaking scales<sup>7</sup>. Flatness can also be spoiled by higher-order non-renormalizable terms. A generic potential during inflation is a sum of flat direction potential  $V(\phi)$  and the inflaton potential  $V(I)$ , where

$$V(\phi) \sim (1/2)m_{3/2}^2|\phi|^2 + C_H H^2|\phi|^2 + \lambda^2|\phi|^{2n-2}/M_p^{2n-6}, \quad (2)$$

where  $H$  is the expansion rate, and  $n = 4, \dots, 9$  (I neglected the A-terms, for a full flat direction potential, see<sup>2</sup>),  $m_{3/2} \sim O(1)$  TeV (m-SUGRA),  $\lambda \sim O(1)$ , and  $C_H \sim O(1)$  for a minimal Kähler structure. For no-scale SUGRA, one-loop correction gives  $C_H \sim 0.01$ <sup>8</sup>. For our discussion we assume the Hubble induced mass term is vanishing, e.g.  $C_H \approx 0$ , the situation may arise in no-scale SUGRA model, or inflation driven by D-term potential, or a non-minimal Kähler structure. For  $C_H \neq 0$ , the flat direction simply rolls down the potential during inflation, leaving rather uninteresting consequences.

Not all F- and D-flat directions can act as a condensate, only one out of nearly 300 MSSM flat directions can obtain a large vev, because not all of them are independent, for e.g.  $LH_u$ ,  $LLe$ ,  $H_uH_d$  are not independent.

#### 4. Density perturbations

The initial density perturbations generated by the MSSM flat directions is in the form of isocurvature perturbations, because there are at least two fields dynamically evolving, inflaton and the flat direction. For multi fields the total curvature perturbations,  $\zeta$ , outside the horizon is not constant, because there is a pressure difference between the fields which is evolving. This isocurvature perturbations has to be converted into the adiabatic perturbations. This happens after inflation,  $H$  drops fast, when  $m_{3/2} \sim H(t)$ , then the flat direction starts oscillating and decaying into MSSM degrees of freedom<sup>9</sup>. However it is important that its energy density must dominate while decaying. This puts severe constraint on MSSM flat direction, only candidates are  $LLddd$  (lifted by  $n = 7$  non-renormalizable operator,  $H_u LLLddd$ ), and  $QuQuQue$  (lifted by  $n = 9$  operator,  $QuQuQuH_d ee$ )<sup>10</sup>.

The curvature perturbations for the flat direction is given by  $P_\zeta^{1/2} \approx rH_*/\pi\phi_*$ <sup>11</sup>, where  $r = 3\rho_\phi/(4\rho_\gamma + 3\rho_\phi)$ , where  $\rho_\gamma$  is the energy in the radiation bath from inflaton decay. Non-Gaussianity of the produced perturbation requires the curvaton to contribute more than 1% to the energy density of the universe at the time of decay, that is  $r_{\text{dec}} > 0.01$ <sup>11</sup>. During inflation only the non-renormalizable term dominates, Eq. (2), which gives an interesting relationship

$$H_* \sim \beta^{(1/n-3)} \delta^{(n-2/n-3)} M_p, \quad \phi_* \sim \beta^{(1/n-3)} \delta^{(1/n-3)} M_p, \quad \delta \sim (H_*/\phi_*).$$

where  $*$  denotes the epoch during inflation when modes are leaving the horizon, and the amplitude of the fluctuations,  $\delta = \delta\phi/\phi_* \sim 10^{-5}$ . The value of  $\beta \ll 1$  ( $\beta$  depends on the superpotential which lifts the flat direction) arises from  $V''(\phi) \sim \beta^2 H_*^2 \ll H_*^2$ . The spectral index of the perturbations is then given by<sup>11</sup>

$$n_s - 1 \sim 2\dot{H}_*/H_*^2 + (2/3)(V''(\phi_*)/H_*^2) \sim (2/3)\beta^2, \quad (3)$$

where we assumed that the Hubble expansion is nearly a constant,  $\dot{H}/H^2 \approx 0$ . Note that for  $\beta < 0.1$ , the spectral index is close to the observable limit  $n_s = 0.99 \pm 0.04$ <sup>3</sup>.

In an another paradigm shift, it is even conceivable to dump the inflaton energy density outside our world, e.g., in an anti-de-Sitter (adS) background

geometry, where the observable world is a 3-dimensional hypersurface (realizable in string theory via stack of  $D3$ ,  $D7$  branes), the inflaton energy density can be dumped near the adS throat<sup>12,13</sup>. For the observable world the dumped energy will be red-shifted because of the non-trivial warped background. This miniscule energy (depending on the size of the overall manifold, string coupling and string scale) could even answer our quest for the dark energy. In such a set up, after inflation, the only energy density is left behind is the condensate energy. In this case the best candidate for the flat direction is the MSSM Higgses  $H_u H_d$ <sup>12</sup>. In both the cases, discussed above, the reheat temperature,  $T_{rh} \leq 10^9$  GeV<sup>10,12</sup>, is below the gravitino overproduction limit<sup>14</sup>.

Yet another possibility arises when the inflaton and the MSSM flat directions are not completely independent, they can have non-renormalizable coupling. In which case the inflaton coupling to the MSSM obtains fluctuating inflaton coupling which gives rise to the spatial fluctuations in the decay rate and the reheating temperature<sup>15,16</sup>.

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